

The Impact of Fermi on the Study of Gamma-ray Bursts

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Recent *Fermi* results have focused attention on gamma-ray burst's (GRB) prompt emission phase, which is rich in phenomenology and poorly understood. The broad band spectra observed by *Fermi* does not fit into any of the frameworks of existing theoretical models. Thus, *Fermi* results force new thinking of questions that were thought to be solved. I highlight here the basic open questions prior to the launch of *Fermi*, key *Fermi* results, and new theoretical ideas that emerged following these results. These include: (I) renewed interest in magnetized outflows as a way to understand the dynamics and composition; (II) interest in photospheric emission, in particular ways to broaden "Planck" spectrum to resemble the observed "Band" spectrum; (III) The puzzling origin of the high energy (LAT) photons, first observed in short GRBs; and (IV) new methods to estimate the Lorentz factor of the outflow.

1. Introduction

The data provided by *Fermi* on GRBs in the past three years since its launch, are extreme in richness and quality. *Fermi* new capabilities had focused attention on the prompt and early afterglow emission phases in GRBs, which show rich phenomenology. Both the quality and quantity of the data enable, for the first time, systematic study of these early emission phases.

Study of these phases is very important due to its very wide applicability: during these early phases, one studies the latest stages of the collapse and the earliest stages of the jet formation - before self-similar motion wipes the initial outflow conditions. This is also what makes this study so challenging: as no two GRBs are similar, it is very difficult to draw firm conclusions which are true to *all* GRBs.

Confronting *Fermi* data with theoretical models show the deficit of the latter. The data provided by *Fermi* did not fit into any of the existing theoretical models; in some cases, it was in contradiction to the theoretical expectations. This fact motivated new ideas, which are continuously being raised and discussed. With this respect, the contribution of *Fermi* is enormous - questions which were thought to be solved are proven not to be.

In this review, I discuss some of the key *Fermi* results, from a theoretician's perspective. I start by stating in §2 what we are certain about, and then in §3 what are the basic theoretical questions which need to be answered. In §4 I highlight some of *Fermi*'s unexpected results, and their influence on our understanding of GRBs. I then describe in §5 the recent theoretical progress motivated by these results, and try to point towards additional observational signatures that could help resolve basic theoretical problems.

2. GRBs: basic, unquestionable facts

The field of GRBs is characterized by many uncertainties and a huge divergence within the GRB population, both in spectral and time domains. Nonetheless, after two decades of extensive research there are few basic, unquestionable facts, which are common to all GRBs and should be addressed by any theoretical model. It is firm today that GRBs are:

1. Transient in nature: no repetition was ever found. The duration of the prompt phase vary a lot from burst to burst, and can last between a fraction of a second to hundreds of seconds. During this phase, the light curve is highly variable.
2. Extragalactic objects, originating at cosmological distances.
3. Very energetic, releasing (isotropically equivalent) energy of $\sim 10^{49} - 10^{55}$ erg in γ -rays alone.
4. The observed spectrum is non-thermal. In the vast majority of bursts, it has a broken power law shape (the "Band" function, named after the late David Band), peaking at sub-MeV, with a fairly sharp decline at higher energies (see Figure 1). In a small fraction, about $\sim 5\%$, photons were seen up to very high energies, ~ 30 GeV. In few bursts there is an additional, high energy component which is not related to the original "Band" function [1].
5. Relativistic expansion: very high Lorentz factor, $\Gamma \sim 10^2 - 10^3$ is required by observations of high energy photons. This has solid confirmation by the existence of afterglow emission, which follows the interaction of the relativistic ejecta with the ambient medium.
6. There are two populations of bursts, separated by their duration and hardness: the "short/hard" and the "long/soft" [2]. There are

firm evidence that long GRBs are connected to supernovae [e.g., 3]. Indirect evidence suggest that short GRBs originate from binary mergers [4], but no conclusive evidence yet [e.g., 5, 6].

3. Open questions prior to the launch of Fermi

Based on these observational facts, a general framework, the GRB “fireball” model¹ emerged nearly two decades ago, and still serves as the main theoretical framework.

The basic phases of this model are best described in terms of the *energy flow*. The progenitor, which can be either a collapse of a massive star or merger of binaries, releases gravitational energy (E_G).² While part (or even most) of this energy is released in the form of neutrinos or magnetic flux, a significant part is eventually converted to kinetic energy (E_k): this is the jet formation episode.

At a second stage, part of the jet kinetic energy is being dissipated (say, fraction $\epsilon_d \leq 1$). Several mechanisms were suggested for this dissipation, such as internal shocks [7] or magnetic reconnection [8, 9]. Uncertain part of the dissipated energy ($\epsilon_d E_k$) is used to produce population of energetic, non-thermal electrons, which emit the observed γ -rays. Other parts may be used to generate magnetic field, accelerate protons or simply heat the plasma. The remains of the kinetic energy is gradually released at later times, producing the observed afterglow.

This general framework has two strong advantages. First, it is consistent with all past and current observations. Second, the existence of the afterglow was predicted by this model, and hence its detection is a strong confirmation.

This model, however, suffers several very serious drawbacks. First, the model is heuristic in nature, and many of the details of the physics are missing. For example, the details of the jet formation which result in the very high Lorentz factor, $\Gamma \sim 10^2 - 10^3$ as compared to AGNs, in which $\Gamma \leq 30$ are not explained. Another example relates to the physics of particle acceleration to non-thermal distribution, which, although inferred by the observations, is not well understood. Other parts of the model have very little predictive power: for example, internal dissipation is required to explain the variable light curve, however,

the model does not provide any prediction of the dissipation processes, such as their radii, amount of kinetic energy that is dissipated, etc.

Thus, major theoretical tasks are to “fill the gaps” in this basic framework. Very broadly, the theoretical efforts are focused on:

1. Understanding the nature of the progenitor.
2. Understanding jet launching mechanism, and the role played by ν 's, photons and magnetic field in this process.
3. The dynamics of GRB jets: what causes these jets to have such a high Lorentz factor, as opposed to jets in other objects, which have much lower Lorentz factors?
4. Jet composition: what is the role played by leptons, hadrons and magnetic field?
5. Understanding the nature of the dissipation mechanism that leads to the emission of γ -rays.
6. Radiative processes, and physical explanation to the broad band spectrum observed.

In addition to these basic GRB physics questions, other questions relate to the connection between GRBs and other objects of interest, such as stellar evolution, host galaxies, binary evolution, gravitational waves, cosmic rays etc. Additional questions relate to the use of GRBs as probes of basic physics and cosmology: use of GRBs as standard candles [10], providing limits on violation of Lorentz invariance [11] etc.

In the past few years there were major theoretical efforts aiming at addressing these questions. As unfortunately I am not able to summarize all of the recent works within the page limits of the current proceedings, I will focus on works which were directly influenced by recent *Fermi* results. Obviously, as we are observing photons, there is no direct way to determine the answers to the questions outlined above, but these have to be deduced indirectly.

4. Fermi key results

After three years of operation, one can summarize *Fermi* key results as follows. The detection rate of the GBM detector is ~ 250 bursts/year, which is about the expected rate. However, the LAT detected only ~ 10 bursts/year, namely $\approx 5\%$ of GBM bursts are observed in the LAT energy range (~ 40 MeV – 300 GeV; see Omodei's talk). This fraction is significantly lower than the pre-launch expectations; however, as will be discussed below, these expectations were based on mathematical extrapolation of lower energy data, which did not carry strong physical reasoning. On the other hand, the fact that ~ 30 GeV photons were

¹Interestingly enough, alternative scenarios, such as the “Cannonball” model, or the “fireshell” model, have similar basic ingredients.

²Another potentially significant source of energy is the spin energy of the central object.

observed can be translated, via the opacity argument [12] into a stringent constraint on the Lorentz factor of (LAT) bursts, $\Gamma \sim 10^3$, which is higher than previously thought.

The spectral properties of the vast majority of *Fermi* bursts are very similar to the spectral properties of the *CGRO-BATSE* bursts. Most GBM bursts are well fitted with a “Band” function, peaking at sub-MeV. The low energy spectral index is, on the average, somewhat harder than that of the *BATSE* bursts, yet within the errors (photon index $\alpha = -0.95 \pm 0.23$ vs. $\alpha = -1.00 \pm 0.31$ for the bright bursts)[13].

LAT bursts, on the other hand, show a different behavior. Several bursts show evidence for a separate, extra high energy component, that is not part of the original “Band” fits. This was observed both in long bursts (e.g., GRB090902B) [14] and in short bursts (e.g., GRB090510) [15]. However, this was not observed in the majority of the LAT bursts [1]: for example, the spectrum of GRB080916C did not show evidence for an extra component [16]. These qualitative spectral differences are shown in Figure 1. It should be stressed that such differences could not have been seen by *BATSE*, due to its limited spectral coverage, 30 – 2000 keV.

In spite of the fairly low statistics, a clear trend had emerged: in most (but not all) bursts the high energy (LAT) photons arrive at a *delay* of few seconds with respect to the lower energy (GBM) photons. This delay is observed in both long and short GRBs: e.g., the long GRB080916C, and the short GRB090510. In addition to the delay in the onset of the high energy photons, another important result is their extension to late times: LAT photons are observed to be long-lived. High energy photons are frequently continuously observed for few seconds after the decay of the low energy (GBM) photons. Both these features are demonstrated by the temporal behavior of GRB090510 presented in Figure 2.

5. Theoretical implications

5.1. Spectral properties: hard spectral slopes

The fact that the low energy spectral index is, on the average, similar to the low energy spectral index observed by the *BATSE*, implies that it is too hard to be accounted for by (optically-thin) synchrotron emission [19, 20]. This serves as a strong motivation for alternative scenarios.

Recently, several works considered the effect of inverse-Compton (IC) scattering on the *synchrotron* spectra [21, 22, 23, 24]. Due to the Klein-Nishina suppression, energetic electrons are cooled less efficiently than low energy electrons, resulting in a hardening of the electrons distribution. The resulting synchrotron

emission can be as hard as $F_\nu \propto \nu^0$ under the appropriate conditions.

A lot of theoretical attention was given to contribution from the photosphere, which is arguably the most natural explanation to the hard slopes observed, being inherent to the “fireball” model [25, 26, 27, 28]. The basic idea is very appealing: while no combination of synchrotron spectra can produce slopes harder than $F_\nu \propto \nu^{1/3}$ (in the “slow cooling” regime) or $F_\nu \propto \nu^{-1/2}$ (in the “fast cooling” regime), it is possible to produce the harder “Band” function by broadening Planck spectra. Thus, in recent years, theoretical research in this field was focused on mechanisms that can broaden Planck spectrum.

Spectral broadening can be achieved in two ways. First, energy dissipation below the photosphere produces a population of non-thermal electrons, which emit radiation. Such a dissipation can result from internal shocks, magnetic reconnection or collisional heating. Since the dissipation is assumed to take place in region of high optical depth, multiple Compton scattering dominates the spectra, which can be broader than Planck if the optical depth is not too high. This scenario gained broad interest recently [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40]. Second, broadening is caused by contribution of off-axis emission [41, 42, 43, 44, 45]. While off-axis photons are sub-dominant as long as the inner engine is active, they broaden the Planck spectrum. They become dominant once the inner engine decays. Quantitative results depend on the jet geometry.

On the observational side, following pioneering works by *Ryde* [46, 47], in recent years there are several successful attempts to identify a thermal (Planck) component in existing broad-band spectra [17, 38, 48, 49, 50, 51, 52]. Such a “pure” Planck spectra can be expected if (I) energy dissipation occurs very deep in the flow or only outside the photosphere, and (II) the photospheric radius is close to the coasting radius, so that adiabatic energy losses are small. The clear identification of this component, albeit in only a limited number of bursts, is a strong motivation for continuous theoretical research.

5.2. High energy emission: spectral properties and delayed onset

Understanding the origin of the high energy (LAT) emission is difficult, because of the confusing results: while in many LAT bursts (e.g., GRB080916C) the high energy component smoothly connects to the low energy part, and is part of the “Band” function, in others (e.g., GRB090902B) it is spectrally separated (see Figure 1).

Clearly, emission from the photosphere cannot, by itself, explain a separated spectral component at these energies. Thus, within the context of the photospheric

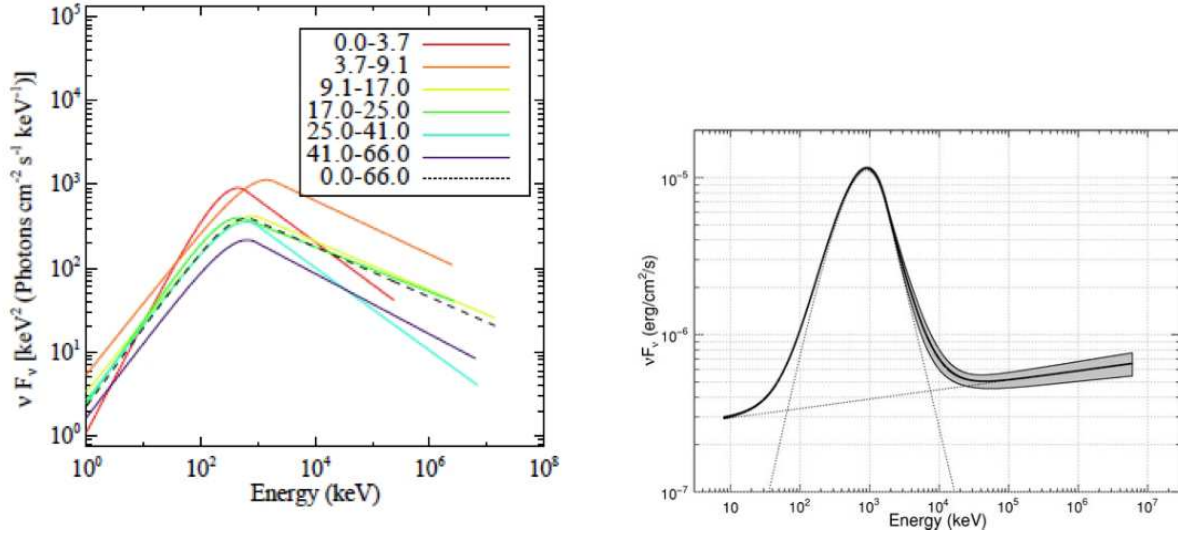


Figure 1: Spectra of GRB080916C (left, taken from [1, 16]) at different times and GRB 090902B (right, taken from [14]) show a clear, “typical” broken power law shape, peaking at sub MeV, which is known as the “Band” function. There are, however, qualitative differences: In GRB090902B there is an extra, high energy power law, which cannot be fitted with the “Band” spectrum. The sub MeV peak of the emission is very hard, and can best be fitted by a (multi-color) “Planck” function [17, 18]. The spectrum of GRB080916C, on the other hand, is much flatter, and does not require an extra high energy component.

emission models, a second episode of energy dissipation above the photosphere is required in order to explain \sim GeV emission. Inclusion of this additional dissipation can provide very good fits to the data [18]. This scenario is thus consistent with a separation of the spectral component (as in GRB09092B), as well as with the observed delay of the high energy component. Alternatively, the spectral separation of this component may result from a different origin: it was suggested by several authors that while the “Band” part has a leptonic origin, the high energy part may have hadronic origin [53, 54, 55], or may originate from an expanding “Cocoon” [56].

Many LAT GRBs show high energy emission which seems to be smoothly connected to the low energy part, hinting towards common origin (e.g., GRB080916C). The temporal evolution of the decay at these energies, $F_\nu(t) \propto t^{-1.5}$ is consistent with having external origin. Thus, it was proposed by several authors [57, 58, 59, 60, 61, 62] that the high energy component results from energy dissipation by the external shock, similar to the afterglow emission. Thus, according to this view, the high energy emission is in fact part of the afterglow emission, which naturally explains the extension of the emission to late times. On the other hand, a detailed spectral analysis showed that at least part of the GeV emission must have internal origin [63, 64]. Moreover, the smooth spectral extrapolation to the low energy part (the Sub MeV peak and below) implies that either the low energy part also has an external origin, in which case it is dif-

ficult to explain the hardness of the spectral slopes, or that both components “conspire” to smoothly match. Over all, the origin of the GeV emission is still uncertain, and more data is needed.

5.3. Jet Composition and dynamics

As photospheric emission is an inherent part of the classical, baryonic “fireball” model, the fact that it is not observed in most bursts challenges this model. The lack of observed photospheric signal in GRB080916C was used to argue in favor of magnetically-dominated outflow [65].

This idea has a firm theoretical basis. Significant developments in numerical GRMHD codes in the past few years enabled a detailed study of jet launching [66, 67, 68]. These works mark the first steps towards realization of the Blandford and Znajek [69] and Blandford and Payne [70] mechanisms, in which the magnetic field plays a crucial role as energy mediator in jet production. Thus, if indeed these are the jet launching mechanisms that work in nature, one expects highly magnetized outflow, $\sigma \equiv u_B/\rho c^2 \gg 1$ close to the jet-launching site. Here, u_B is the (electro-) magnetic energy density and ρ is the baryon density.

Motivated by these results, in recent years there were numerous attempts to study the properties of magnetized outflows. While studies in this field are not new and were done prior to *Fermi* era (e.g., [8, 71, 72]), *Fermi*’s recent results stimulated a re-

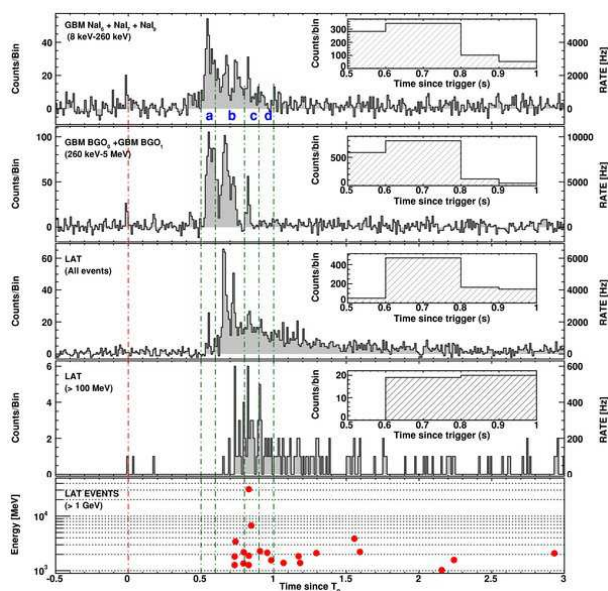


Figure 2: Lightcurve of the short burst GRB090510 [15] show clear indication of lag in the onset of the high energy (LAT) photons with respect to the lower energy (GBM) photons, by \sim second. Moreover, high energy emission is long lasting: it extends several seconds after the GBM emission decayed. Both the delay and the late emission are typical for many LAT bursts.

newed interest. Research in this field is currently focused on bridging the theoretical gaps in all aspects of magnetized jet physics: (I) creation of relativistic jets in magnetars [73, 74, 75, 76]; (II) dynamics, energy dissipation and efficiency of magnetic reconnection and magnetized shock waves [77, 78, 79, 80, 81, 82]; (III) particle acceleration in magnetized outflows [83, 84], and (IV) the resulting radiative signature [32, 82, 85, 86]. While the current picture is far from being complete, this is a very active research field.

Finally, detection of high energy photons imply, using the opacity argument, high Lorentz factor, $\Gamma \simeq 10^3$ in few LAT bursts [33, 87]. These values are more than an order of magnitude higher than the typical Lorentz factor in AGNs, $\Gamma \leq 30$, and are not theoretically understood. Several works in recent years were focused on finding new methods to determine the Lorentz factor [88], and to find better constraints on the Lorentz factor of the outflow. Indeed, a more advanced analysis using the assumption of multi-zone emission, or taking geometrical corrections showed that the Lorentz factor may not be as high, and may be limited to few hundreds [89, 90].

6. Summary

Fermi results focused attention on the *prompt* emis-

sion phase in GRBs, which is rich in phenomenology, and is poorly understood. While the general “fireball” framework that was constructed during the 90’s still holds, a lot of gaps in the theoretical understanding still exist.

In recent years significant theoretical progress was made in understanding the physics of the prompt emission. I highlighted here a few active research areas in which, to my opinion, *Fermi* results were very influential.

1. *Progenitor, jet launching and composition.* A renewed interest in magnetized models and magnetars as GRB progenitors had emerged, largely stimulated by recent *Fermi* results. Research is focused on all aspects of (relativistic) magnetized outflows, from jet launch, dynamics to the observed signal.
2. *Radiative processes and spectral properties.* A lot of effort was given to understanding the role played by photospheric emission, and in particular mechanisms that can be used to broaden Planck spectrum, so that it will resemble the observed “Band” spectra. Effort is given to understanding signatures of magnetized outflows.
3. *Jet dynamics and origin of high energy emission.* In spite of numerous efforts, the origin of high energy emission is still unclear. This is because of the confusing results, which show in many bursts smooth spectral extrapolation between the high energy and lower energy photons, while a separate component in other bursts.
4. *Accurate measurement of the Lorentz factor.* The high values of $\Gamma \sim 10^3$ inferred by the existence of high energy photons are challenging. They motivated a more careful analysis of the data, which indeed show somewhat lower values. Still, no theoretical understanding of these values exists.

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